Credibility of 21st Century numerical simulations in A/C crash and impact analysis

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ABSTRACT

After a brief reminder of general specifications in commercial aircraft crash survivability regulation, the following paper addresses several issues related to the use of dynamic and crash tests as validation cases for numerical simulations, the current place of the modern numerical simulations in A/C crash analysis, and their main limitations today. A focus will be made on this last question, in order to review well known sources of error in these numerical simulations, recall now long established good practices in Crash FE modelling, and question the concept of a test-free verification and validation process (for virtual testing). Final conclusions and outlooks end the paper, with shorter term and more realistic objectives being optimistically claimed: make the actual crash simulation codes and good practices an acceptable mean to establish "robustness demonstrations" (by parametric/ sensitivity numerical analysis) of the crash performance of modern aircraft design.

KEYWORDS: *Safety, Aircraft, Numerical simulations, crashworthiness, good practices.*

1 INTRODUCTION

Aviation is one of the safest public transport means today. To reach such a performance, aircraft safety mainly relies on experience feedback and a set of constantly evolving rules which concern the flying products and operations. In the course of events which punctuated the aeronautics history, aircraft certification rules progressively improved. This is especially the case in the field of crash and survivability, which is identified as a specific topic for instance in the FAR 25 and CS 25 (large civil aircraft) documents. An advisory group was recently set up in the USA by the FAA, to address the question of - and identify - beneficial research activities in the field of civil aircraft crashworthiness. As a consequence, some French aircraft manufacturers also proposed to the French CORAC organization (Council for Civil Aviation Research) to unite their efforts in order to better cover possible future regulation evolutions in the crash safety domain. A transverse "Crash and Survivability" theme was introduced in 2013 within the CORAC overall roadmap. The results of their discussions were presented to the French DGAC (French General Civil Aviation Authorities), which in parallel proposed medium and long term research topics to be studied in the future, among which the challenging one of the full aircraft numerical crash simulation, to better cover the crash domain (and to avoid costly experimental approach). This research axis clearly invokes the question of the credibility of current and future numerical simulations for A/C crash and impact analysis.

Considering CS25 [1], the first crash requirement concerning the occupants safety is to design the aircraft in order to limit passengers' g-levels to acceptable levels under "survivable" crash conditions (mainly characterized by a given vertical crash velocity or a given variation of vertical velocity during crash). Concerning the fuselage airframe, the requirement is to preserve cabin integrity (avoid material and structural failure that would endanger directly or indirectly the passengers' life) under specified loads or load factors encountered during the previously specified survivable crash scenarios. In short, “Factors in crash survivability” are: (1) retention of items of mass, (2) maintenance of occupant emergency egress paths, (3) maintenance of acceptable acceleration and loads experienced by the occupants, and (4) maintenance of a survivable volume. Last, aware of the difficulty of demonstrating compliance to such crash specifications, the formulation used by the authorities in introduction in the general CS25.561 paragraph is that the aircraft design should “give each occupant every reasonable chance of escaping serious injury in a minor crash landing”. In fact, a demonstration with respect to crash conditions is only mandatory for specific components/ parts (e.g. seats, landing gears and fuel tanks) in EASA CS 25. Nevertheless, because of the specificities of composite materials and structures compared to metallic ones, special conditions have been issued to adapt and qualify the previous specifications to better deal with composite commercial aircraft safety (B787 [2], A350 [3]).

The present paper is based on a bibliographic review and on ONERA’s in-house expertise (developed for a long time in collaboration with Airbus Aircraft) in the field of crashworthiness of commercial aircraft. Its aim is to synthetize the current state-of-the-art and remind general and good practices in the field of experimental and numerical crash safety demonstration.

2 DYNAMIC AND CRAST TESTS AS VALIDATION CASES FOR NUMERICAL SIMULATIONS

2.1 About crash tests

Crash tests (see Fig. 1) were progressively used to support the development and assessment of the emerging numerical tools for crashworthiness analysis [5]. As the modern finite element codes capabilities still often fail in predicting very complex dynamic nonlinear and rupture behaviours of complex structures, such tests still permit for instance to compare the characteristic responses of composite versus metallic aircraft, and support the industry in new design choices [6].

Figure 1: Scale 1 crash test at DGA TA (1995) – EU TIM-Crash project

The objective of controlled crash tests (in test centers or labs) is to give access to accurate data, meaning in terms of controlling and measuring the crash conditions (attitude, velocities, etc), and in terms of better instrumenting, recording and ensuring the collection of mechanical or video data from expensive tests [7] [8] [9]. Then analytical and numerical models and tools can be more confidently developed and assessed [10] [11].

2.2 About the building block approach

A modern strategy (similar to the building block approach) has been proposed for quite a long time to study crashworthiness of fuselage structures using numerical analysis [12]: cheaper complementary testing means with smaller and different capacities compared to the “full scale” ones are put in place to perform extensive test campaigns, before any expensive full scale guided crash tests on full aircraft section is done. The test strategy [13] usually relies on static and dynamic mechanical characterization of materials (various test means), on bending/ compression tests (hydraulic machines) of components, and on static (hydraulic machine) and dynamic (drop tests) crush tests (vertical) of subfloor sections (incl. stiff floor beams). All the test results are used to progressively develop and validate the numerical models (scale models as in Fig. 2 can also be used to validate the numerical models). For this purpose, the different tests are instrumented to measure either displacements, or deformations, or forces, or structural and passengers (dummies) accelerations.

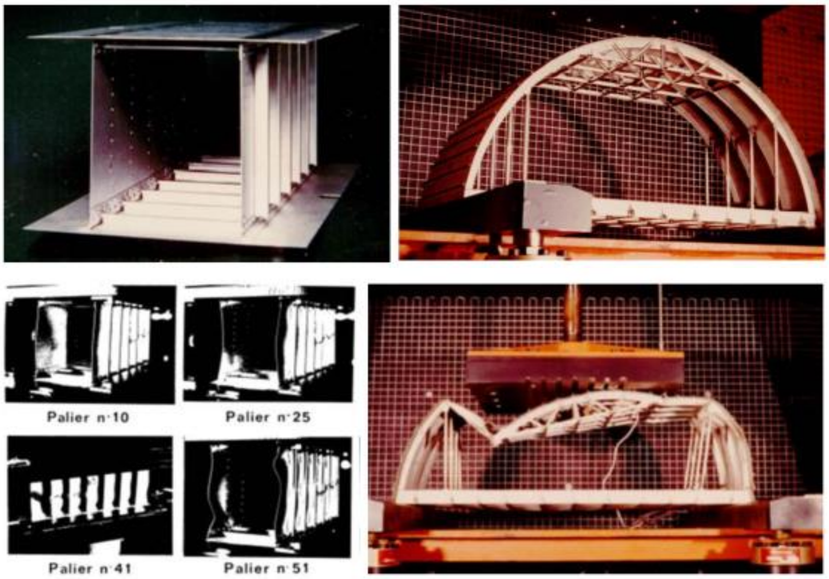

Figure 2: Dynamic crush tests of scale models of structural parts of various complexity (ONERA – French DGAC contracts)

2.3 Good practices in dynamic and crash testing

Progressively, good practices and recommendations were established concerning analogic then digital dynamic crash test data acquisition, filtering and sampling. Among these good practices and recommendations for the verification and filtering of crash test experimental data, one can find: (1) integration of raw unfiltered acceleration signals into velocity, to check validity/ consistency of data thanks to analysis of global values such as impact duration, onset rate and mean acceleration, then determine proper filtering characteristics to be used on the raw temporal data, (2) ruling out erroneous/ questionable experimental data (saturation, interferences, etc), (3) caring about aliasing effects when digital sampling is used for computerizing data, and (4) use of normalized CFC or SAE data filters (forward and backward, etc) [14] [15]. Of course, the same process and means should theoretically be (systematically) applied to numerical simulations accelerations to properly verify then compare with experimental data.

3 THE PLACE OF THE NUMERICAL SIMULATIONS IN A/C CRASH ANALYSIS

3.1 General considerations

The development of numerical methods and tools for crashworthiness analysis includes a lot of different topics beside the question of modelling the (dynamic) nonlinear and rupture behaviour of materials. The tremendous progress made for 30 years on these different topics mainly came from research works done by the applied mathematics community (structural analysis by finite element codes), and by the pioneer defense and automotive industry (crashworthiness and ballistic impacts using explicit resolution schemes).

Concerning the commercial aircraft industry, since full scale crash tests such in “operational conditions” are far too difficult and costly as [16] [17] (compared to the automotive industry) to be performed any day, numerical simulation models cannot easily be calibrated according to test results:

the exigence in terms of intrinsic numerical model "fidelity" and prediction/ extrapolation "capability" is then much higher before one can use numerical simulation for aircraft crash design or certification purposes. Note that two different kinds of numerical approaches can be used, either "coarse" [15] [18] (globally representative) to evaluate gross vehicle response, or "detailed" [19] [20] (but not fully reliable because of local high non-linearities) to study the behaviour of critical components.

3.2 Application of numerical simulations

Injuries, seats and dummies

For crash survivability, many works on seats deal with the reduction of paxs acceleration and are at the moment disconnected from the airframe certification requirements which concern the preservation of the airframe structural integrity (evacuation, secondary impacts) [21]: for instance normalized loads factors (accelerations) are taken as inputs to design the seat-dummy dynamic systems (e.g. 16 g input triangular shape at the seat attachment points). The design of seats clearly benefitted from the use of advanced material models and numerical simulation capabilities in the last decades.

Engines, luggage bins and fuel tanks

Specific CS 25 crash requirements also exist that concern aircraft engines, fuel tanks and various structural components such as luggage stowage bins in cabin, and a long list of works may be found which are focusing on these topics. Of course the FE tool is also used to numerically study the structural behaviour of these specific and complex components (e.g. luggage bins under dynamic crash loads), but the final objectives are quite different compared to usual "crashworthiness" analysis: sizing (strength) at the "attachment points" for the stowage bins for instance [22], and absence of rupture and leakage for the fuel tanks [23].

Airframes (fuselage)

No airframe (fuselage) crash certification is really imposed, but substantiation is required (relative "as safe as" comparison with previous certified aircraft of the same category). The rule then says that the aircraft manufacturer ("applicant") is responsible of the substantiation method (test, modelling or both), which means that the certification authorities do not favor any kind of experimental or numerical tool in this matter [3] [4].

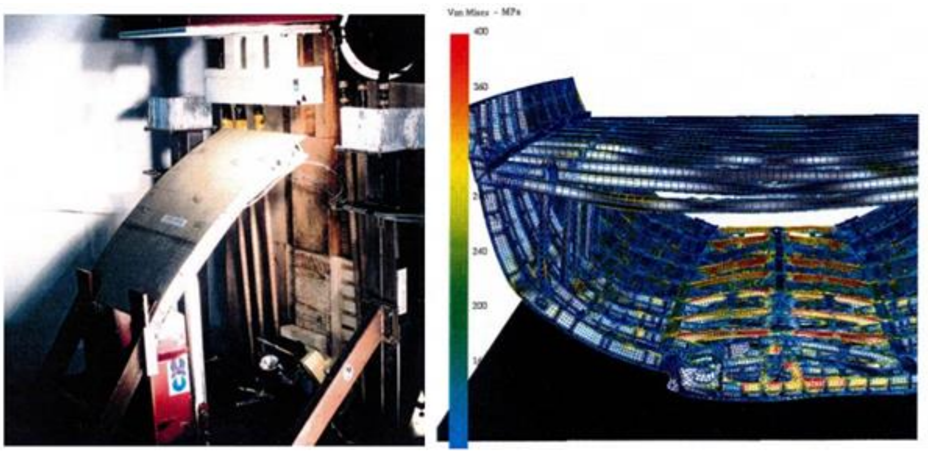

Figure 3: Examples of sub component dynamic test (left, EU TIM-Crash project) or numerical simulations (right, ONERA FE model – DGAC contract)

4 LIMITATIONS OF NUMERICAL CRASH SIMULATIONS

4.1 Errors in numerical simulations

Bibliography

As already mentioned, general practices for full scale FE crash simulation can be found in [18], describing well the modelling exercise, and detailing the numerous approximations made in coarse models, which are sources of numerical errors and differences with the experimental results. In [18] the author describes what has since become a standard coarse modelling methodology in terms of geometry description, finite elements formulations, use of beam elements to model some parts (longitudinal stringers) without meshing their profiles (hence avoiding small elements), in terms of mesh size, mass calibration or addition (for components, fluids, etc), and in terms of management of contacts, consideration of gravity, etc.

Caution regarding optimistic conclusions

Then, when one comes to numerical results, despite the use of coarse meshes and simple material models, quite satisfying results (envelopes) are often reported in the literature to compare well with experimental data (with - or sometimes even without - initial calibration of the model). In such cases, a great attention should be paid to the filtering process which has been applied to the experimental and numerical results, because it can totally compromise the soundness of the results if not properly justified.

Sources of errors

When deviations between crash test and simulations are reported, a key question is "where does the difference come from" [19]? In fact simulation errors may come either from uncertainties/ variations in the mechanical material or structural parameters, but also from previously mentioned model approximations. These errors can be "corrected" thanks to models calibration if test results are available. But note that calibration can always be successful if enough model parameters are tunable, which is generally the case when complex structures are studied. Unfortunately the verification that the invoked calibrated parameters (e.g. thicknesses of components, Young moduli, etc [24]) are the physical reason for the initial test vs numerical FE model deviations can rarely be established. The question becomes: how to prove that the calibration method leads to a physical (and not a fake) validated model/ result, which can then be confidently used for other crash configurations?

In the end, recommendations but not predictions can usually be given, and final engineering/ expert judgment is often still necessary to validate the conclusions of the numerical crash simulations.

4.2 Good practices in Crash FE numerical simulations

Bibliography

In parallel to the development of the numerical simulation capabilities and tools to simulate the crash response of aircraft structures, the basic questions of evaluating the correctness (verification) of the modelling process and of physically validating (against reference test data) the obtained numerical results were addressed and discussed by several authors. Some methods, good practices and recommendations they made for the exploitation (evaluation and correlation with respect to test results) then validation of numerical models against test data [14] [15] are hereafter reminded.

About explicit FE codes (verification)

First, because of the specificities of crash problems, because the explicit codes resolution algorithms are in many aspects not energy conservative, and because the studied mechanical systems can be either open or closed (e.g. in case of enforced displacement load function), basic verification steps are always needed before trusting any explicit FE simulation result: they mainly rely on the analysis of the energy balance throughout the computation (kinetic, internal, potential, contact, total), external forces work, etc.

Crash simulation validation

Second, tests and simulations should not only be simply compared thanks to dynamic temporal data obtained by different "gauges" (accelerometers, strain, dummies, etc) but also if possible in terms of frequency (Fast Fourier Transform, Power Spectral Density) and modal responses (for instance by using standard techniques/ tools in structural dynamics analysis). All the more as large differences (curve to curve) often appear between the crash experimental and simulation temporal data (e.g. noisy acceleration "time histories") because of the complexity of studied structures and models. So dedicated "data reduction" or specific "numerical interpretation/ exploitation" techniques should be applied to these dynamic data before really concluding about the "representativeness/ fidelity" of the simulation compared to the test.

Global quality checks

For instance, before validating a crash simulation, common sense "quality checks" have to be done [25] by plotting experimental and numerical velocity decrease (integration of unfiltered accelerations) and rebound (in case of a vertical crash test), and by comparing the impact duration (from V0 to 0 m/s) and the average acceleration. Persisting large differences according to such "indicators" in the end would then either reveal data bad sampling/ filtering or unacceptable modelling errors or approximations.

Filtering and exploitation of dynamic results

Last, once these elementary checks passed, proper filters can be applied, and peak acceleration values, maximum Dynamic Response Index (DRI), Head Injury Criterion (HIC), etc, can be analysed to give more sense to the measured data. Concerning the filtering operation, because of the high frequency band contained in the numerical data, the lower (but still consistent with the experimental structural dynamic analysis discussed before) the low-pass filter applied to the numerical data, the more meaningful the comparison with the test results (filtered the same way, of course).

4.3 Verification and validation without test data

Analysis vs Prediction

When pre-test numerical simulations of structural crash tests are challenged, without knowing the crash results, a refined FE modelling strategy is generally preferred. This trend developed more recently in the 2000's compared to the coarse modelling one because of obvious computing capabilities limitations in the 80's.

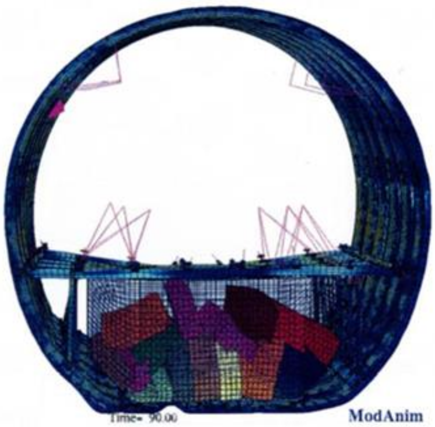

Figure 4: Virtual test of a metallic fuselage section with its luggage container (ONERA – DGAC contract)

Rules of the art

Here a very specific problem emerged, which concerns the non-convergence of numerical results according to the increasing mesh size when highly nonlinear softening phenomena (such as plasticity, damage, rupture) have to be modelled (mesh sensitivity issue). The first care to take concerning this particular point when no test results are available is to use as regular a mesh size as possible for all the structure (self-consistency), to use the same mesh size used to identify/validate the material properties from the coupon tests in the full structure model, and to build on previous experimentally validated modelling experiences (expert rules, building block approach). Other ways to get rid of these mesh size dependencies are still at the research stage (e.g. non local models).

How to avoid opening a Pandora box

Then, not knowing with certainty the first order parameters which will influence the results, everything has first to be taken into account e.g. the nature of the soil/ ground, the rivets/ joints, etc. This leads to huge FE models. To reduce the number of driving parameters and the problem dimension, sensitivity studies must then be carried out. Once an acceptable model reduction has been reach, and as long as the quality of the model is good enough (see previous "quality checks"), acceptable qualitative and quantitative results can be obtained at the global structural level. At the local level, good curve to curve correlations (in terms of local mechanical measurements such as filtered accelerometers, strains, etc) can also be reached but only in areas where simple ruin modes/ scenarios develop (simple or no local failure).

4.4 Ultimate barriers before getting fully predictive crash simulations

Assessed capabilities

If the previously discussed good practices are respected, it seems that modern FE crash codes could be used to perform crash analysis and sensitivity studies as long as possible unstable failure modes are avoided by design (a simple, robust and deterministic structural behaviour develops). The modern commercial codes have already been successfully applied for limited objectives (e.g. relative comparison of different component or aircraft design), in the case of a safe airframe with deterministic rupture during crash for instance. But one major difficulty appears when numerous, random, and unstable ruptures develop, in joints or details in primary structures for instance, which can hardly be avoided in current aircraft airframe under realistic crash situations: crashworthiness turns back to be a real numerical challenge.

Figure 5: Full scale FE model of a modern commercial aircraft for ditching analysis (ONERA – EU SMAES project)

Expectations and future improvements

Besides, probabilistic methods and modelling of uncertainties are stringent issues when numerical simulation (using FE methods) of the dynamic behaviour and mostly rupture of structures is concerned. Note first that probabilistic methods do not introduce new structural analysis techniques, but depend heavily on the state-of-the-art structural analysis codes which are the heart of the numerical solutions. Probabilistic methods have already been used for structural static design (no-failure analysis) [26] [27] but almost never for (uncertain) aircraft crash analysis [28]. First they should then take into account random variations of materials rupture criteria, of geometrical and boundary conditions, etc, to compute probability distributions of data to be compared to survivability criteria (g levels, cabin deformation and rupture, etc). Then if one really wants to introduce statistics and probabilistic analyses in crash survivability studies, not only the material scatter and structural random variables should be considered, but also the random crash conditions (e.g. velocity, terrain, etc), occupant protection/restraint systems performances, and human physiological tolerances. It is difficult to totally justify a probabilistic study only limited to the material/ structural aspects when so many other random parameters exist that could have a major/ first order influence on crash survivability. The main difficulty concerning the probabilistic methods/ approaches turns in the end to be that the number of design parameters (uncertain or deterministic) for aircraft structures is still too huge to be dealt with considering the available computing powers today. In this field, one should know that the current research effort is to study/ develop probabilistic methods that can handle more than 100 design parameters, not to increase the size and accuracy of models.

5 CONCLUSIONS

Good practices have been proposed for crash simulations to increase confidence in the quantitative results: they deal with both the verification and the validation of the numerical models. Though these good practices have been defined, a comprehensive point of view or a clear V&V strategy is often missing in many studies reported in the literature: no FE model quasi-static nonlinear analysis and/or FE linear modal analysis (implicit codes), no FE sensitivity studies (crash models), no comparison either with pyramidal numerical of experimental reference results, etc, generally complete the analyses. This fact greatly limits the reach of the conclusions of many works, even in "quite simple" application cases.

Prediction capabilities under certain conditions (truncated test/analysis pyramid)

If the good practices are respected, and as long as quite simple stable structural ruin modes are considered, numerical sensitivity studies using modern explicit FE codes have a sense to estimate the relative performance of different design concepts. Coarse FE mesh can even be used in this case, and complex material models are useless (regarding the other simplifications or approximations made).
It was the case for the crash justification of the Airbus A350 aircraft which was performed according the virtual testing approach presented in Figure 6. The main interest of this approach was the quality and robustness of the prediction of the various ruin modes (mostly highlighted and "calibrated" from lower pyramid levels specimens) while also having a FE numerical model available at higher levels able to predict the global kinematics and major mechanisms which develops during the crushing event.

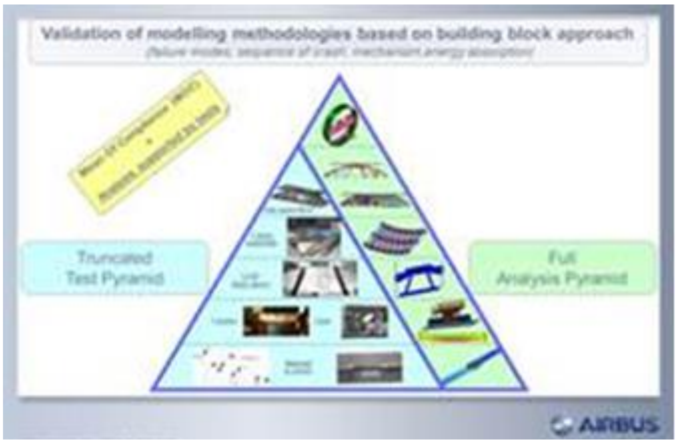

Figure 6: Virtual Testing Approach for the crash justification of the Airbus A350 fuselage

Numerical prediction of complex structures and rupture scenarios possible but at a high CPU cost (no barrel test required by EASA for A350-900, even the composite frame version)

When complex structures and failure modes develop, knowledge (post-test or expert) based FE simulations are often reported in journal papers to succeed in agreeing with the tests or the expert expectations), be the FE model coarse or fine. Note nevertheless that few comments are generally made about this validation being obtained after a possibly long and costly trial and error exercise (the total number of runs and CPU hours needed before reaching a satisfying agreement). Also many calibration possibilities (material mechanical parameters, components thicknesses, structural details, joints, ground/ soil model, etc) exist in complex models beside knowledge based ones which can improve simulation results wrt expected ones on false mechanical basis/hypothesis. Without proper safeguards (such as the previously mentioned Virtual Testing Approach proposed by Airbus, in Figure 6), "blind" calibration should not be considered as acceptable.

A system complexity ontop a multiphysical complexity

In the end the question of the broadness of topics to embrace before reaching fully predictive commercial aircraft crash simulations has to be clear in one's mind (Pandora box): level of detail in terms of structural geometry and design (contacts, joints), representative boundary conditions (ground, soil), material behavior laws (nonlinear, rupture, strain rate sensitivity, etc), numerical soundness (mesh sensitivity, ringing) and efficiency (CPU cost), verification and validation (V&V) methodology, etc. A short term and more realistic objective can be more pragmatically to definitely make the actual crash simulation codes and good practices an acceptable mean to establish "robustness demonstrations" (by parametric/ sensitivity numerical analysis) of the crash performance of modern aircraft design.

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REFERENCES

1. CS 25; "Certification specifications - part 25"; Regulation; EASA; www.easa.europa.eu;
2. FAR 25; "Federal aviation regulations - part 25"; Regulation;FAA; www.faa.gov;
3. FAA-2007-NM368 / n° 25–362–SC; "Boeing Model 787–8 Airplane – Crashworthiness"; Special Conditions; FAA; www.faa.gov;
4. FAA–2013–0892 / n° 25–537–SC; "Airbus A350–900 Airplane - Crashworthiness, emergency landing conditions"; Special Conditions; FAA; www.faa.gov;
5. E. L. Fasanella, E. Alfaro-Bou; 1986; "Vertical Drop Test of a Transport Fuselage Section Located Aft of the Wing"; NASA Technical Memorandum, NASA-TM-89025;
6. Jackson K. E.; 1997; "Analytical crash simulation of three composite fuselage concepts and experimental correlation"; *Journal of the American Helicopter Society*; **7**(3); pp. 981–986
7. V. Vaughan, E. Alfaro-Bou; 1976; "Impact Dynamics Research Facility for Full-Scale Aircraft Crash Testing"; NASA Technical Report; NASA TN D-8179;
8. Jackson K.E., Boitnott R. L., Fasanella E. L., Jones L. E., Lyle K. H.; 2006; "A summary of DOD-sponsored research performed at nasa langley's impact dynamics research facility"; *Journal of the American Helicopter Society*; **51**(1); pp. 59–69
9. J. Fabis, D. Delsart; 2014; "Sub-cargo demonstrator crash test results"; ONERA Technical Report; RT 1-23233.2;
10. Jackson K.E.; 2201; "Impact testing and simulation of a crashworthy composite fuselage concept"; *International Journal of Crashworthiness*; **6**(1); pp. 107–121
11. Arnaudeau F., Mahé M., Deletombe E., Le Page F.; 2002; "Crashworthiness of aircraft composite structures", *ASME International Mechanical Engineering Congress and Exposition*; New Orleans (USA); November;
12. J. D. Cronkhite, V. L. Berry; 1982; "Crashworthy airframe design concepts – fabrication and testing"; NASA Technical Report; NASA-TR-3603;
13. Heimbs S., Hoffmann M., Waimer M., Schmeer S., Blaurock J.; 2013; "Dynamic testing and modelling of composite fuselage frames and fasteners for aircraft crash simulations"; *International Journal of Crashworthiness*, **18** (4); pp. 406-422

14. Lyle K. H., Bark L. W., Jackson K. E.; "Evaluation of test/analysis correlation methods for crash applications"; *Journal of the American Helicopter Society*; **47**(4); pp. 233–242
15. K. E. Jackson, E. L. Fasanella; "Crash simulation of vertical drop tests of two boeing 737 fuselage sections"; FAA Technical Report; DOT/FAA/AR-02/62;
16. W. H. Reed et al.; 1965; "Full-scale dynamic crash test of a douglass dc-7 aircraft"; Aviation Safety Engineering and Research; FAA Technical Report; FAA ADS-37;
17. W. H. Reed et al.; 1965; "Full-scale dynamic crash test of a lockheed constellation 1649 aircraft", Aviation Safety Engineering and Research; FAA Technical Report; FAA ADS-38;
18. Adams A., Lankarani H. M.; 2003; "A modern aerospace modeling approach for evaluation of aircraft fuselage crashworthiness"; *International Journal of Crashworthiness*; **8**(4); pp. 401–413
19. Hashemi S. M. R., Walton A. C.; 2000; "A systematic approach to aircraft crashworthiness and impact surface material models"; *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*; **214**(5); pp. 265–280
20. Liu X. C., Sun X. S.; 2015; "Drop test and crash simulation of a civil airplane fuselage section"; *Chinese Journal of Aeronautics*; **28**(2); pp. 447–456
21. R. G. W. Cherry, K. Warren, A. Chan; 2000; "A benefit analysis for aircraft 16-g dynamic seats"; FAA Technical Report; DOT/FAA/AR-00/13;
22. Heimbs H., Vogt D., Hartnack R., Schlattmann J., Maier M.; 2008; "Numerical simulation of aircraft interior components under crash loads"; *International Journal of Crashworthines;*, **13**(5); pp. 511–521
23. Luo C., Liu H., Yang J.-L., Liu K.-X.; 2007; "Simulation and analysis of crashworthiness of fuel tank for helicopters"; *Chinese Journal of Aeronautics*; **20**(3); pp. 230–235
24. Horta L.G., Reaves M.C., Annett M.S., Jackson K. E.; 2011; "Multi-dimensional calibration of impact dynamic models", *Conference Proceedings of the Society for Experimental Mechanics Series*; **4**; pp.1–20
25. Lyle K.H., Bark L.W., Jackson K. E.; 2002; "Evaluation of test/analysis correlation methods for crash applications"; *Journal of the American Helicopter Society*; **47**(4); pp. 233–242
26. M. C. Shiao, C. C. Chamis; 1992; "Probabilistic evaluation of a fuselage-type composite structures"; NASA Lewis Research Center; NASA Technical Report; NASA TM-105881;
27. L. W. Long, J. D. Narciso; 1999; "Probabilistic design methodology for composite aircraft structures"; Northrop Grumman; FAA Technical Report; DOT/FAA/AR-99/2;
28. K. H. Lyle, S. L. Padula, A. E. Stockwell; 2003; "Application of probabilistic analysis to aircraft impact dynamics"; NASA Langley Research Center; NASA Technical Report; AIAA–2003–1482;
29. Deletombe E.; 2016; "PHYSAFE – General bibliographic review on crashworthiness of metallic commercial aircraft"; ONERA The French Aerospace Lab; ONERA Technical Report; DMAS RT 2-23324;